NEOGENE TECTONIC EVOLUTION OF THE BETIC CHAIN: INSIGHTS FROM PALEOMAGNETIC, STRUCTURAL ANALYSES, AND LABORATORY MODELS

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Abstract: Based on a critical revision of the available structural and paleomagnetic data coupled with results from laboratory models on oceanic subduction, we suggest that the curvature of the Gibraltar Arc has been achieved throughout opposite vertical axis rotations on the two arms of the arc. Paleomagnetic rotations have been measured in the late Miocene sediments both in the Betics and in the Rif chain, providing a significant rejuvenation of the age of vertical axis rotation. Laboratory models show that the trench roll-back mechanism of a narrow subducting lithosphere can be a valuable mechanism to generate curved structures, mainly caused by toroidal return flow in the upper mantle. Such mechanism can be also extended to other Mediterranean arcs, such as the Calabrian Arc, where a clear relationship between trench-retreat and arc bending has been largely accepted. We suggest that slab roll-back pursued also after the late Miocene, but at a reduced rate and is now almost ceased. Today, the regional present-day kinematics of the western Mediterranean region is characterized by a small (~ 5 mm yr^{-1}) west-northwest motion of the Nubia plate respect to the Eurasia plate.

Key words: Gibraltar Arc, Betics, Neogene, analogue modeling, paleomagnetism, slab roll-back.

Resumen: En función de la revision crítica de los datos estructurales y paleomagnéticos disponibles, junto con los resultados de modelos experimentales sobre subducción oceánica, sugerimos que la curvatura del Arco de Gibraltar se ha alcanzado en sus dos ramas mediante rotaciones verticales de sentido opuesto. Las rotaciones paleomagnéticas se han medido tanto en Béticas como en el Rif en sedimentos del Mioceno superior, demostrando que la edad de la rotación según un eje vertical es significativamente más jóven. Los modelos de laboratorio muestran que el mecanismo de retroceso de una fosa en una zona de subducción litosférica estrecha puede constituir un mecanismo capaz de formar estructuras arqueadas, cuyo origen estaría ligado al flujo de tipo toroide que se genera en el manto superior. Este mecanismo puede extenderse a otros arcos Mediterráneos, como el Arco de Calabria, en el que se acepta comúnmente que existe una relación entre el retroceso de la fosa y el arqueamiento del arco. Sugerimos que el retroceso de la litosfera en la zona de subducción continuó después del Mioceno superior con una velocidad inferior, estando ahora casi finalizado. En la actualidad la cinemática de la región occidental del Mediterráneo se caracteriza por el movimiento moderado (~ 5 mm/a) de la placa de Nubia hacia el oeste-noroeste, con respecto a la placa Euroasiática.

Palabras Clave: Arco de Gibraltar Arc, Béticas, Neógeno, modelización analógica, paleomagnetismo, retroceso de la zona de subducción.

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The Betic chain and the Gibraltar Arc have been the focus of an active scientific debate during the last two decades, giving rise to several and often contrasting hypotheses concerning their tectonic setting and geodynamic evolution. In particular, open questions still concern the tectono-metamorphic history of the inner metamorphic domain, and the timing and mechanisms related to the formation of the Gibraltar Arc and the Alboran basin. These key issues also bear fundamental implications for the tectonic and geodynamic reconstructions of the Mediterranean region during the Neogene.

The complexity of the Gibraltar Arc, similarly to other Mediterranean Arcs, arises from the coexistence of curved mountain belts and back-arc basins which synchronously developed, in a plate-tectonics scenario dominated by the Africa-Eurasia convergence. In fact, over the whole Mediterranean region, the Alpine belt formed a «snake-shaped» belt given by tight arcs with a westward (Gibraltar Arc, Western Alpine Arc), eastward (Calabrian Arc, Carpathian Arc) or south-westward (Hellenic Arc, Cyprus Arc) concavity. Those structures are kinematically inconsistent with the relative motion of the Africa plate respect to Eurasia, as derived by plate tectonics reconstructions (Dewey *et al.*, 1989) or by GPS data (McClusky, *et al.*, 2003; D'Agostino and Selvaggi, 2004; Biggs *et al.*, 2006). Delamination, removal of the mantle lithosphere, subduction and lateral extrusion are all viable mechanisms commonly proposed to explain the formation of the arcs formed at high angle with respect to the convergence direction. In particular, an attractive and popular solution for their origin, firstly proposed by Malinverno and Ryan (1986) for the Calabrian Arc, is based on the idea that the origin of the Mediterranean arcs and related back-arc basins are driven by differential roll-back of dense and narrow subducting slabs, resulting from the progressive fragmentation of the subducting African plate (Faccenna *et al.*, 2004; Frizon de Lamotte *et al.*, 1991; Gutscher *et al.*, 2002; Lonergan and White, 1997; Morales *et al.*, 1999; Royden, 1993). The fragmentation of the subducting lithosphere and the formation of isolated slabs reflect the strong lateral heterogeneity of the Eurasia-African plate boundary, characterised by the presence of small pieces of oceanic remnants intervening between continental blocks (Dercourt *et al.*, 1989).

During the last years, we have approached the Betic region by means of structural, paleomagnetic and analogue modeling studies to contribute to the comprehension of the tectonic evolution of the Gibraltar Arc. The aim of these studies was to put constraints on the mode of exhumation of the inner metamorphic domain (Alpujarrides Complex) and to define the Neogene timing and style of rotations in the frame of the geodynamic evolution of the Betics and of the western Mediterranean region (Funiciello *et al.*, 2003; Faccenna *et al.*, 2004; Rossetti *et al.*, 2005; Mattei *et al.*, 2006; Cifelli *et al.*, 2008). In this contribution, after reviewing the literature data, we use these results to support subduction roll-back of a fragmented subducting slabs a viable mechanism to explain the origin of the Gibraltar Arc and of the Alboran basin. In particular, we suggest that this mechanism process pursued also after the late Miocene, but at a reduced rate and now virtually ceased.

Geological background

The Betic Cordillera is traditionally subdivided into three main structural domains (García-Hernández *et al.*, 1980): the Internal Zones (Andrieux *et al.*, 1971) the Flysch Trough Units, and the Prebetic and Subbetic Zones (Comas *et al.*, 1992) (Fig. 1).

The Alboran Domain is located onshore and offshore in the inner part of the arc. It consists mostly of metamorphic units, which constitute the remnants of a Paleogene orogen (Azañón *et al.*, 2000). The Flysch Trough Units are constituted by siliciclastic sediments of Cretaceous to Early Miocene age, deposited in a deep marine or oceanic setting near the northern African margin (Didon *et al.*, 1973). They outcrop in the western part of the Betic chain and form actually an inactive accretionary prism, whose structural trend is mainly NNW–SSE to N–S directed (Luján *et al.*, 2003). The Subbetic and Prebetic Zones represent the outer margin of the chain and are formed by Mesozoic and Tertiary sediments deposited in basinal (Subbetic) and

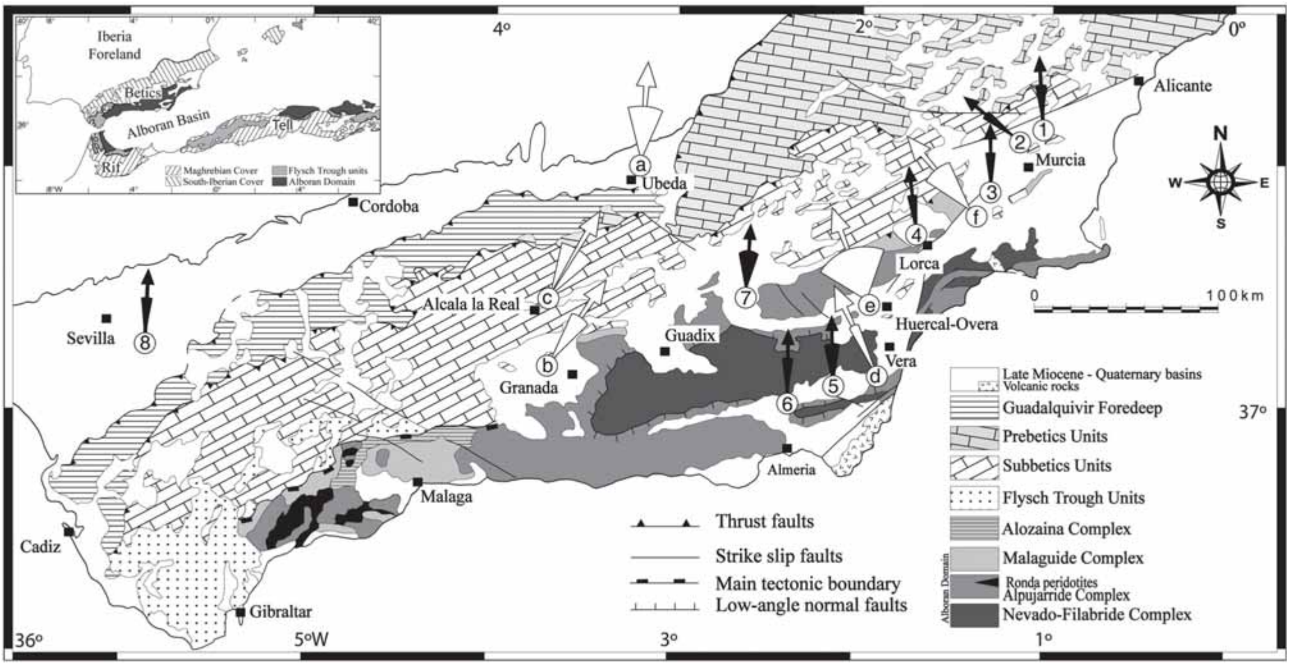

Figure 1.- Schematic geological map of the Betic Cordillera, where paleomagnetic declinations (and relative confidence limits) from Neogene sediments in the Betic chain are reported (from Mattei *et al.*, 2006). White arrows come from Mattei *et al.* (2006) and indicate cumulative paleomagnetic declinations for each study basin (a: Guadalquivir Basin, b: Granada Basin, c: Alcalá la Real Basin, d: Vera Basin, e: Huercal-Overa Basin, f: Lorca-Tercia Basin). Black arrows come from previous studies and are indicative of mean paleomagnetic declination deduced in single magnetostratigraphic sections: 1) Dinarés-Turell *et al.* (1999); 2) and 3) Garcés *et al.* (2001); 4) Krijgsman *et al.* (2000); 5) Sierro *et al.* (2001); 6) Krijgsman *et al.* (2001); 7) Garcés *et al.* (1997); 8) Krijgsman and Garcés (2004). Inset shows main tectonic domains in the Western Mediterranean.

shelf (Prebetic) environments of the rifted paleomargin of South Iberia. These rocks were detached from their Hercynian basement from early Miocene onwards, and formed a NNE–SSW to NE–SW trending fold-and thrust belt, with associated foredeep and foreland basins along its outer margin (Guadalquivir Complex and Guadalquivir Basins, respectively). Extensional tectonics during Miocene times played an important role in the development and evolution of the sedimentary basins that lie over the internal domains of the Betics (*et al.*, Platt *et al.*, 1998; García-Dueñas *et al.*, 1992), including the present-day Alboran Sea Basin (Watts *et al.*, 1992; Comas *et al.*, 1999). In particular, the formation of the Alboran Sea was largely coeval with the development of the Flysch Trough Complex, Subbetic and Prebetic fold-and-thrust belt. Finally, during the late Miocene, the Gibraltar region experienced a drastic modification of the tectonic regime, possibly related with the decline of the roll-back processes in the Gibraltar Arc subduction system (Faccenna *et al.*, 2004; Duggen *et al.*, 2004), meanwhile the Africa–Eurasia plate convergence vector changed from a N-S direction to a NW-SE one (*et al.*, Dewey *et al.*, 1989). As a consequence, the whole Betics and the Alboran Sea Basin underwent a complex pattern of compressional and strike-slip tectonics which, in some cases, inverted previous extensional structures (Watts *et al.*, 1992; Comas *et al.*, 1999). Volcanism accompanied and postdated Neogene extension, with calc-alkaline, potassic and basaltic volcanism scattered across the eastern sector of Alboran Sea and Betic–Rif chain.

In the following sections we describe some aspects of the Betic orogen geology, which have been the main subject of our research.

Main scientific results from the «Roma Tre» Research Group

We had the opportunity to be introduced to the geology and tectonics of the Betic chain by Prof. Víctor García-Dueñas, in the frame of a collaborative research project between the University of Granada and the University of Roma TRE. Professor García-Dueñas showed us some of the spectacular outcrops of the Sierra Nevada and participated to the first paleomagnetic sampling. His work has not been fundamental only to understand the Betics geology, but it is dense of new and original concepts that are now fundaments and essences of mountain building process. This article is the opportunity for all of us to thank Prof. García-Dueñas to whom this article is dedicated.

The metamorphic units of the Alboran Domain

The Alboran Domain represents the core of the Betic orogen and consists of three main tectono-metamorphic complexes, which from top to bottom are: the Malaguide, Alpujarride and the Nevado-Filabride complexes. The Malaguide Complex retains Variscan orogenic features in the Paleozoic rocks, and its Mesozoic to Paleogene cover did not suffered pervasive alpine deformation and/or metamorphism (Chalouan and Michard, 1990). Both the Alpujarride and the Nevado-Filabride complexes instead retain subduction zone metamorphic signatures, with metamorphic gradients typical of the alpine orogenic cycle.

The Alpujarride complex consists of an inverse-order post-metamorphic nappe stack, made of different units. From bottom to top and in general order of increasing metamorphic grade (Azañón *et al.*, 1994) they are: Lújar-Gádor, Escalate, Salobreña, Herradura and Adra units. Where complete, the lithostratigraphic sequence includes Paleozoic basement rocks and Permo-Triassic metapelites and quartzites. Carbonate rocks, Middle and Upper Triassic in age (Braga and Martín, 1987), represent the uppermost levels. The ultramafic rocks of the Ronda region consists of independent tectonic slices, included at the bottom of the highest Alpujarride unit (*et al.*, Tubía and Cuevas, 1986; Balanyá *et al.*, 1997). The Alpujarride Complex records a polyphase alpine metamorphic history. The metamorphic climax corresponds to a high pressure/temperature (P/T) metamorphic gradient (16-17°C km^{-1}, with peak conditions at 1.2 MPa and 550°C), followed by nearly isothermal decompression during which the main, second phase S-L fabric developed (*et al.*, Bakker *et al.*, 1989; Goffé *et al.*, 1989; Azañón *et al.*, 1998). An increase in temperature during the last stages of the exhumation of these rock types, indicating heating during decompression, has been described in rocks drilled in the Alboran Sea (Platt *et al.*, 1998).

The Nevado-Filabride complex consists of the superimposition of two main tectonic units (Martínez-Martínez *et al.*, 2002 and references therein): the upper Mulhacen and the lower Ragua (ex Veleta) units. Metamorphic climax is distinctly different in the two units, since whereas the Mulhacen unit contains eclogitic lenses (*et al.*, Morten *et al.*, 1987; Bakker *et al.*, 1989; Puga *et al.*, 2002) with a metamorphic climax equilibrated at 2.0 MPa and 550-600°C (López Sánchez-Vizcaíno *et al.*, 2001), peak metamorphic conditions in the Ragua unit was equilibrated within the blueschist facies at about 1.2 Ma and 450°C (Booth-Rea *et al.*, 2003; Augier *et al.*, 2005).

Contacts among these complexes are bounded by two main extensional detachments (Platt and Vissers, 1989; Jabaloy *et al.*, 1993; Martínez-Martínez *et al.*, 2002): the upper bounds contact between the Malaguide and the Alpujarride complex, the lower bounds contact between the Alpujarride and the Nevado Filabride complex. The Nevado-Filabrides crop out at the core of the Sierra Nevada dome (Martínez-Martínez *et al.* 2002).

Timing of the Alpine Metamorphism

An early Miocene cluster of radiometric ages is recorded in most of the rocks of the Alboran Domain on the basis of the simultaneous application of thermochronometres with different closure temperatures (Platt and Whitehouse, 1999; Sánchez-Rodríguez and Gebauer, 2000; López-Sánchez-Vizcaíno *et al.*, 2001; Whitehouse and Platt, 2003; Platt *et al.*, 2003, 2005, 2006). This age cluster has been interpreted either as the evidence for early Miocene high-grade metamorphism in the Alboran Domain and as the evidence for onset of post orogenic extension in the region during the collapse of the chain (Zeck *et al.*, 1992; Platt *et al.*, 1998; Platt and Whitehouse, 1999; Platt *et al.*, 2003), or related to subduction events (Sánchez-Rodríguez and Gebauer, 2000; López-Sánchez-Vizcaíno *et al.*, 2001). Recently, based on Lu-Hf garnet ages from the upper HP units of the Nevado-Filabride Complex, Platt *et al.* (2006) revised the timing of the orogeny in the region and renewed the proposal of early Miocene (18-14 Ma) subduction in the Alboran Domain that involved the Nevado-Filabride complex, following exhumation of the Alpujarride Complex. Despite these contrasting data/interpretations, the timing of the Alpine HP thickening has been generally ascribed to the Eocene based on different arguments (*et al.*, Zeck, 1996; Balanyá *et al.*, 1997; Platt *et al.*, 1998, 2003, 2005; Augier *et al.*, 2005; Rossetti *et al.*, 2005). This age attribution is supported by the presence of metamorphic detritus in Oligo-Miocene sedimentary rock successions surrounding the Alboran Domain (Bourgois *et al.*, 1972; Serrano *et al.*, 1995; Lonergan and Mange-Rajetzky, 1994; Lonergan and Johnson, 1998).

The final cooling at near surface conditions in the Alboran Domain as constrained from fission track thermochronology occurred at around 18-16 Ma for the Alpujarride (Andriessen and Zeck, 1996; Platt *et al.*, 1998; Sosson *et al.*, 1998) and from 12 to 8 Ma for the Nevado-Filabride (Johnson *et al.*, 1997).

Structural architecture

The main rock fabric in the Alpujarride Complex consists of a progressive ductile-to-brittle shearing developed during retrogressive metamorphism and rock exhumation. The syn-metamorphic ductile fabric consists of S-L tectonites developed during regional top-to-the-N/NE shearing (Crespo-Blanc *et al.*, 1994, 1995; Balanyá *et al.*, 1997; Orozco *et al.*, 1998; Rossetti *et al.*, 2005). The significance of this deformation is debated, being interpreted either as related to post-orogenic extension contemporaneous with the formation of the Alboran basin that started some 27 Ma ago (*et al.*, Platt and Whitehouse, 1999), or to syn-orogenic deformation within the Eo-Oligocene accretionary complex (Tubía *et al.*, 1992; Simancas and Campos, 1994; Balanyá *et al.*, 1997; Rossetti *et al.*, 2005). The brittle fabric is consequence of two-stage extensional faulting episode, accommodating early (Burdigalian to Langhian in age) N-S and subsequent (Serravallian in age) E-W extension (Galindo-Zaldívar *et al.*, 1991; García-Dueñas *et al.*, 1992; Jabaloy *et al.*, 1993; Crespo-Blanc *et al.*, 1994, 1995; Martínez-Martínez and Azañón, 1997, 2002).

The main rock fabric in the Nevado-Filabride Complex documents progressive ductile-to-brittle top-to-the-W-SW shearing during exhumation and progressive activation of the extensional detachment tectonics in the Sierra Nevada dome (Augier *et al.*, 2005). Based on Ar-Ar in situ dating of phengites in shear bands this episode of shearing was attributed to the Early-Middle Miocene (20-14 Ma time span), but the attribution to an extensional environment was recently disputed by Platt *et al.* (2006) that instead proposed a coeval subduction event.

Paleomagnetic data from the Neogene basins in the Betics

First paleomagnetic data from the Gibraltar Arc were come mostly from Jurassic to late Cretaceous sedimentary units from external Betics in Spain (Platzman, 1992; Allerton *et al.*, 1993; Villalaín *et al.*, 1994; Platt *et al.*, 1995, 2003; Osete *et al.*, 2004) and External Rif in Morocco (Platzman *et al.*, 1993) and showed mostly clockwise and counterclockwise rotations, respectively north and south of the Gibraltar Strait. Later on paleomagnetic results from internal metamorphic units, which are supposed to be remagnetised during early Miocene, also showed the same opposite pattern of vertical axis rotations along the two arms of the Arc (Feinberg *et al.*, 1996). These paleomagnetic data have been used to suggest that the present-day shape of the Gibraltar Arc is a secondary features achieved throughout large and opposite vertical axis rotations in the Betics and in the Rif sector of the arc, and that these rotations occurred during Oligocene-early Miocene and were almost concluded in the late Miocene times (see Platt *et al.*, 2003 for a critical review on such a dataset). However most of the paleomagnetic data used for such paleotectonic reconstructions come from Mesozoic rocks, leaving the age of the tectonic rotations largely unconstrained.

In fact, the timing of paleomagnetic rotations was based, other than on the geologic and tectonic evolution of the area, on very few and sparse paleomagnetic data coming from Miocene or younger rocks. Allerton *et al.* (1993) analysed Miocene sites founding large CW rotations in sedimentary rocks of Aquitanian age in eastern Betics, while no rotations were measured in one Tortonian site. Platzman *et al.* (2000), Calvo *et al.* (2001) and Platzman and Platt (2004) measured variable amount of CW vertical axis rotation in Lower Miocene mafic dikes in the Malaga and in the Alpujarride regions. In the Murcia-Cabo de Gata region, Calvo *et al.* (1997) measured complex vertical axis rotations (mainly CCW) in Upper Miocene to Pliocene sedimentary and volcanic rocks affected by left-lateral strike-slip faulting. Magnetostratigraphic investigations have been also carried out on Upper

Miocene to Pliocene sedimentary sections in several internal and foreland basins of both the Betics and Rif (Garcés *et al.*, 2001; Dinarès-Turell *et al.*, 1999; Krijgsman *et al.*, 1999, 2000; Hilgen *et al.*, 2000; Sierro *et al.*, 2001; Van Assen *et al.*, 2004). In that case, paleomagnetic data generally show no significant vertical axis rotations since the late Tortonian (Krijgsman and Garcés, 2004).

More recently, in order to better define the age of paleomagnetic rotation during Neogene times, Miocene to Pliocene sediments from some intramontane sedimentary basins located in very different areas of the Betics were investigated. Paleomagnetic results have been obtained from structural domains which experienced different tectonic evolution during the Neogene. In particular, Miocene sediments were sampled in: (i) the Guadalquivir foreland basin, (ii) the intramontane basins of central Betics, and (iii) the sedimentary basins in eastern Betics, which were mainly deformed by strike-slip tectonics. Results from this research, published in Mattei *et al*. (2006), evidence a complex pattern of vertical axis rotations, which took place after the late Miocene (Fig. 1).

A first important constraint about the mechanism which caused vertical axis rotations in the Betics is given by results from the Guadalquivir basin. In such a basin, paleomagnetic results from the Tortonian marls, together with those from Messinian units of the western part of the basin (Krijgsman and Garcés, 2004) indicate that the Guadalquivir foreland basin underwent no rotations since the late Miocene, suggesting that vertical axis rotations related to the bending of the external part of the Gibraltar Arc were confined to the Betic-Rif orogenic wedge.

In the central Betics, significant CW rotations in the Messinian sediments of the Granada basin and in the Aquitanian to Tortonian sedimentary units in the Alcalá la Real basin were measured. These rotations are post-Tortonian in the Alcalá-la-Real basin and post Messinian in Granada basin. Therefore, in both basins these rotations took place after the main compressional event, which lead to the formation of the Subbetic fold-and-thrust belt in the central Betics. Previous works considered that paleomagnetic rotations in Central Betics occurred mainly during the early Miocene and were already completed in the late Miocene (Krijgsman and Garcés, 2004). By contrast, counterclockwise vertical axis rotations were measured in the Middle Miocene-to Lower Pliocene sites in the Lorca and Vera basins and, locally, in the Tortonian units of the Huercal-Overa basin. The rotated sediments are Serravallian to Lower Pliocene in age, and do not show any statistical difference or trend depending from the age or the stratigraphic position of the sampled sites. In particular in the Vera basin, close to the left-lateral Palomares strike-slip fault, 25° of CCW rotations have been measured in Upper Messinian-Lowermost Pliocene sites which suggest that CCW rotations occurred after that time. These CCW rotations have been observed in the different sedimentary basins located along a deformation belt dominated by Late Miocene-Quaternary left-lateral strike-slip faults, which characterized the whole South Iberian continental margin in the region of Almería-Murcia. In this region CCW rotations do not extend to sedimentary basins, which are located far away from the main strike-slip faults (Calvo *et al.*, 1997; Krijgsman and Garcés, 2004), and indicate the occurrence of small, fault-bounded blocks that rotate about vertical axis as a consequence of the activity of these faults. It is worth to note that some of these faults are supposed to be active (Booth-Rea *et al.*, 2004). Consequently, block rotation around vertical axis along left-lateral strike-slip faults could still be an active mechanism in the Almería-Murcia region.

A synthetic geodynamic model

Some geological and paleomagnetic constraints

A synthetic model for the evolution of the Betic Cordillera has necessarily to take into account the following points:

(1) The metamorphic rocks of the Alboran Domain document a polyphase metamorphic history, involving deep-seated burial and exhumation for both the Nevado-Filabride and Alpujarride complex. Based on the available AFT data, exhumation was diachronous (completed at ca. 18 Ma for the Alpujarrides and at 8-12 Ma for the Nevado-Filabrides) and occurred under nearly orthogonal exhumation directions (top-to-the-N/NE for the Alpujarrides and top-to-the-W for the Nevado-Filabrides). Therefore, during the final exhumation of the Nevado-Filabrides, the Alpujarrides already reached the surface and the Nevado-Filabride Complex represented an extensional core complex with respect to the Alpujarride Complex, being the latter an extensional allochtonous translated during ductile-to-brittle top-to-the-W extensional detachment tectonics (Augier *et al.*, 2005);

(2) Top-to-the-west shearing has been also recognized in some of the major contractional structures in the external Betics (*et al.*, Frizon de Lamotte *et al.*, 1991), and are coherent with the westward propagation of the sedimentation in the Guadalquivir foreland basin;

(3) Paleomagnetic data indicate that in the Betic chain a different rotational behaviour can be recognized since Late Miocene onwards. Firstly, the lack of rotation in the Tortonian clays of the Guadalquivir basin indicates that the basin itself represents the northern boundary of the rotating domains of the western Betics. The no rotational behaviour of the Guadalquivir foreland basin mirror the no rotational pat-

tern that have been recently recognized in the Fez-Taza basins (Cifelli *et al.*, 2008; Krijgsman and Garcés, 2004) in the foreland of the Morocco Rif. The absence of significant vertical axis rotations either in the Rif and in the Betics foreland basins shows that paleomagnetic rotations are confined in the orogenic wedge, and do not extend to the Iberia and Africa forelands, which remained almost unrotated. Secondly, the CW paleomagnetic rotations measured in the Upper Miocene units in central part of the Betic chain (Mattei *et al.,* 2006) are coherent with previous paleomagnetic results in the Betics, where clockwise rotations were already documented (Villalaín *et al.*, 1994; Platt *et al.*, 2003). However, the occurrence of such rotations in the Upper Miocene sedimentary units demonstrates that some amount of the measured paleomagnetic rotations are younger than previously supposed and occurred after the main phases of fold-and-belt formation in the Betic chain, which is Oligocene-Middle Miocene (Mattei *et al.,* 2006). The rotational behaviour in the Betic chain mirrors that observed in the Rif chain, which represents the southern arm of the Gibraltar Arc. In fact, recent paleomagnetic data show that Tortonian-Messinian sediments deposited in the thrust-top basins from the external Rif underwent a significant amount (20° in average) of CCW rotations (Cifelli *et al.,* 2008). Third, interpretation of the CCW paleomagnetic rotations measured in the Upper Miocene to Pliocene sediments in the eastern Betics (Vera, Lorca and Huercal-Overa basins) is straightforward as they are clearly related to the presence of a large-scale left-lateral strike-slip fault system. Such CCW paleomagnetic rotations appear to be confined in a narrow belt close to the left-lateral strike-slip fault system and do not appear to extend to the entire eastern Betics, where magnetostratigraphic data, located away from the main left-lateral faults, do not show any significant rotations. Again this behaviour mirrors what has been observed in the Upper Miocene sediments from the post-orogenic basins from the Boudinar-Melilla area, in the Mediterranean side of the Rif, where no paleomagnetic rotations have been recently measured (Cifelli *et al.*, 2008). It is worth to note that a similar pattern of paleomagnetic rotations has been observed in the Calabrian Arc (Cifelli *et al.*, 2007; Mattei *et al.*, 2007 and references therein), where huge and opposite paleomagnetic rotations have been measured in the orogenic wedge, whereas the foreland basins remained almost not rotated. In the Calabrian Arc there are clear geological, seismic and paleomagnetic evidences that the progressive curvature of the arc has been achieved during the Neogene as a consequence of the rapid roll-back of the Ionian slab, a small piece of Mesozoic oceanic lithosphere intervening between the Hyblean and Apulian continental lithosphere, toward the southwest and northeast respectively (Malinverno and Ryan, 1986; and hereafter). In conclusion, the regional distribution and the timing of paleomagnetic rotations evidence that opposite vertical-axis rotations have been measured in the two arms of the Arc and are clearly confined to the orogenic wedge. In terms of subduction geometry and kinematics such result implies that the paleomagnetic rotations have been only measured in the upper plate of the subducting systems, i.e. at the hanging-wall of the trench.

(4) In the Mediterranean region, tomographic images have documented relics of the Tethyan slab system below the Alboran Sea and the Calabrian Arc, which has been interpreted as the remnant of a nearly continuous E-W striking subduction front along the Africa-Eurasia convergence zone (*et al.*, Faccenna *et al.*, 2004; Spakman and Wortel, 2004) (Fig. 2).

A clue from laboratory models

In the Laboratory of Experimental Tectonics (LET) of Roma Tre University several models have been carried out in order to study the subduction process. Results were applied to the Mediterranean area in order to analyze the mechanism governing the slab dynamics and the role of mantle circulation in forming curved features.

Mantle circulation in subduction zones, as inferred by seismological (*et al.*, Savage, 1999; Silver *et al.*, 1991) and geochemical/isotopic/petrologic data (*et al.*, Turner and Hawkesworth, 1998; Wendt *et al.*, 1997), appears as a complex process whose evolution can be explained only using geodynamic models. In particular, analytic, numerical and laboratory models have highlighted that narrow subduction zones like the Gibraltar Arc (width <500 km) are characterized by intense mantle circulation around the slab edges able to strongly affect subduction geometry and kinematics (Dvorkin *et al.*, 1993; Funiciello *et al.*, 2003,2004, 2006; Morra *et al.*, 2006; Schellart *et al.*, 2007). But the simulation of narrow slabs is often difficult since mantle circulation cannot be correctly approached by models assuming a 2D steady state process. In our recent experimental work, we solved this problem by means of three-dimensional dynamically consistent models.

The slab-upper mantle system has been established in a silicone putty-glucose syrup tank model (Fig. 3A; Funiciello *et al.*, 2004). The mantle circulation pattern

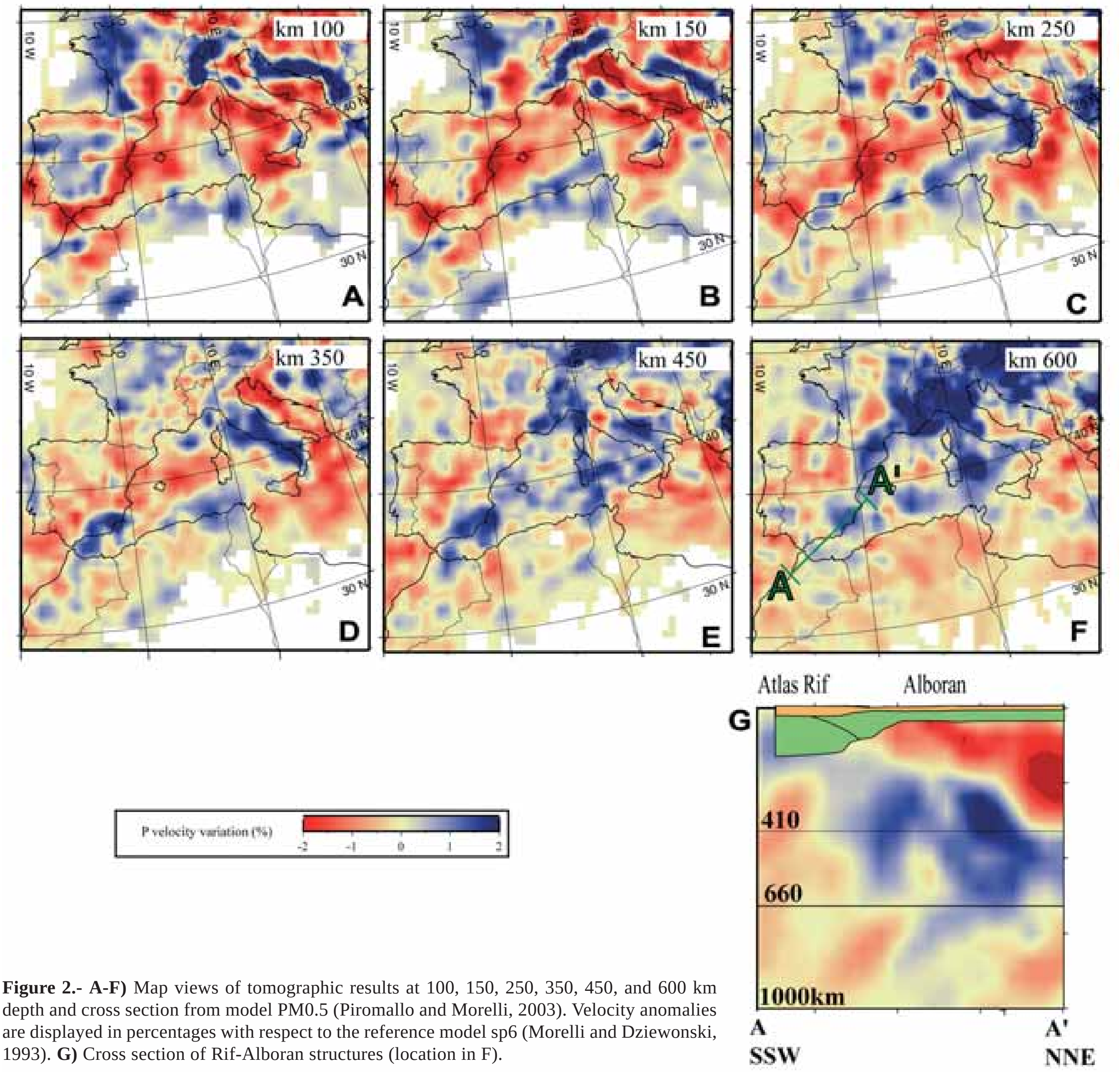

Figure 2.- A-F) Map views of tomographic results at 100, 150, 250, 350, 450, and 600 km depth and cross section from model PM0.5 (Piromallo and Morelli, 2003). Velocity anomalies are displayed in percentages with respect to the reference model sp6 (Morelli and Dziewonski, 1993). **G)** Cross section of Rif-Alboran structures (location in F).

has been quantitatively estimated using a Feature Tracking (FT) image analysis technique (see Funiciello *et al.*, 2006 for details). The effects of plate width and lithosphere-mantle viscosity contrast on mantle circulation and, in turn, subduction geometry and kinematics have been systematically analyzed (Funiciello *et al.*, 2003, 2004, 2006).

The model evolution shows that subduction generates a 3-D time-dependent mantle circulation pattern characterized by the presence of two distinct components: the poloidal and the toroidal one (Fig. 3B, C). Spatial and temporal features of mantle induced circulation have been carefully analyzed obtaining that (1) poloidal and toroidal mantle circulation are both active since the beginning of the subduction process (Fig. 3C). The poloidal component is the answer to the viscous coupling between the slab motion and the mantle. The toroidal component is produced by the lateral slab migration (Fig. 3B). (2) Slab width influences the geometry of mantle circulation and trench velocity. The dimension of the two toroidal cells centred to the plate edges is linearly dependent on trench width (Fig. 3B, C). The trench velocity increases by decreasing slab width. (3) Mantle circulation is episodic. The mantle velocity field increases with time consistently with trench velocity reaching its maximum before the slab interacts with the bottom of the box (Fig. 3C) and getting a steady state value only after the slab-upper/lower mantle discontinuity interaction. Velocity peak at each time is recorded in the region in front of the trench (Fig. 3C) and assume the value of v_t (expressing mantle velocity in terms of percentage of trench velocity allows an easier comparison between experimental results and natural cases). (4) Slab-mantle viscosity contrast and, secondarily, slab width control two first-order features of plate tectonics—the tendency of subduction zones to advance and/or retreat with time and their curvature. In particular, the

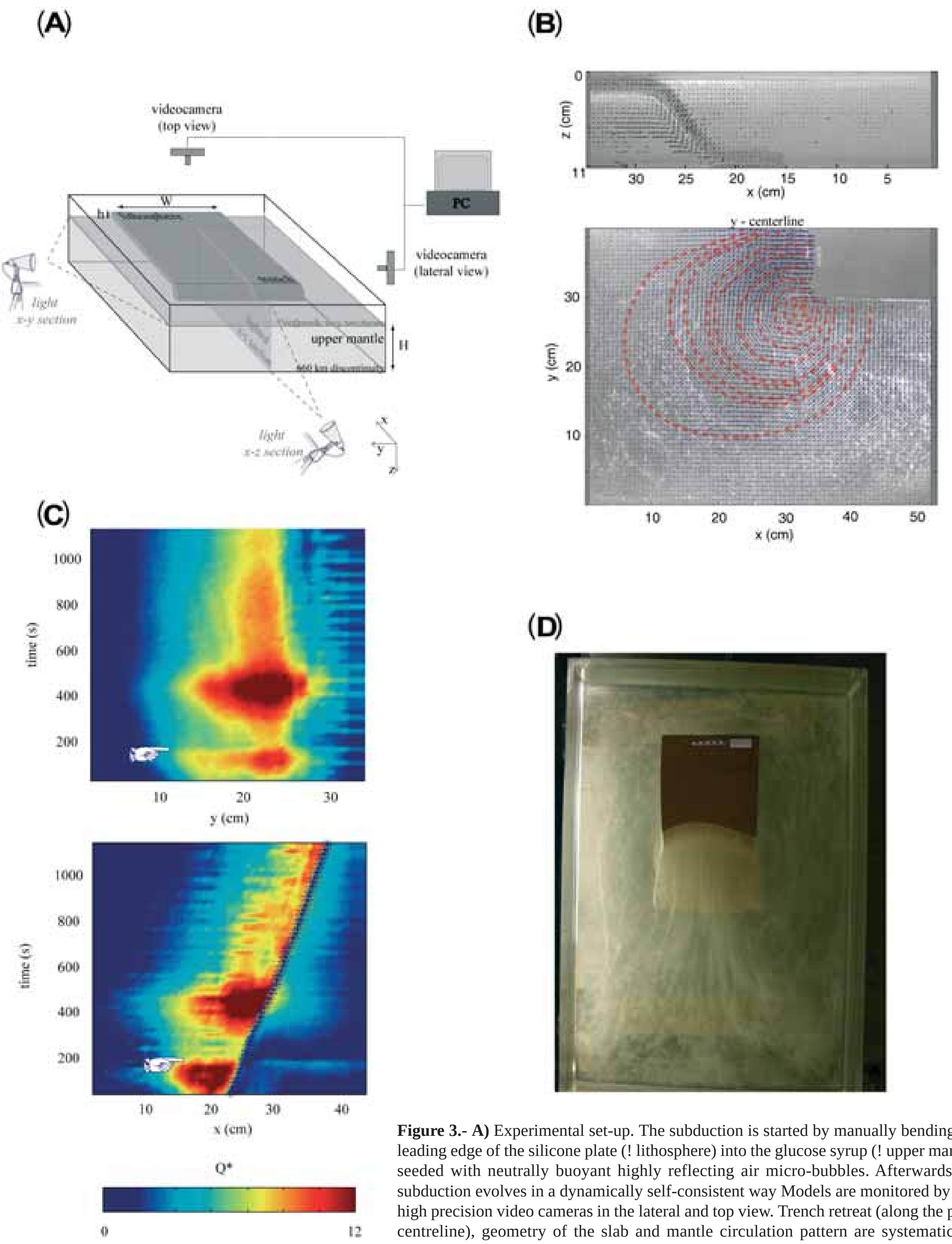

Figure 3.- A) Experimental set-up. The subduction is started by manually bending the leading edge of the silicone plate (! lithosphere) into the glucose syrup (! upper mantle) seeded with neutrally buoyant highly reflecting air micro-bubbles. Afterwards the subduction evolves in a dynamically self-consistent way Models are monitored by two high precision video cameras in the lateral and top view. Trench retreat (along the plate centreline), geometry of the slab and mantle circulation pattern are systematically measured. In particular, the analysis of toroidal mantle circulation is performed onto the x-y plane just below the plate lighted by a neon light sheet of about 5 mm. With the aim to obtain a good resolution, after it has been tested that the analyzed flow is symmetrical along the plate centreline, it is investigated just half of the model. Post-processing the recorded images with the FT technique is possible to obtain a Lagrangian description of the velocity field providing sparse velocity vectors with application points coincident the bright reflecting micro-bubbles. **B)** Velocity field and streamlines of toroidal mantle circulation during the steady state phase as obtained from the FT analysis (see Funiciello *et al.*, 2006 for details). **C)** Time-evolution of normalized linear flow (Q^*) for both x and y component of mantle circulation. Flow components are initially determined as $Q_x = \int| v_y dx |$ and $Q_y = \int| v_x dy |$. Hence, Q_x (Q_y) is computed integrating the absolute value of v_y (v_x) along the x (y) direction. Afterwards, both components are normalized for a reference flow obtained multiplying the steady state trench velocity of the model for the plate thickness. To help interpretation, we marked with a hand the time of occurrence of the slab-660 km discontinuity interaction, when the mantle circulation temporarily slows down. The position of the trench motion at each time is indicated by asterisks on lower panel. This panel allows summarizing the evolution of toroidal flow during the entire evolution of the experiment, highlighting its strong episodicity [periodicity?]. **D)** Top view of an analogue model showing the lateral arcuation of the slab as for lithosphere-upper mantle viscosity ratio ranging between 10^2-10^4.

subduction process can occur with either advancing or retreating trench modes only for $h_l/h_{um} = 10^2\text{-}10^4$. Narrow\thin\heavy plates favour the retreating mode, while wide\thick\light plates prefer to advance (see Bellahsen *et al.*, 2005 for details). This peculiar viscosity range allows also obtaining the slab curvature during the subduction process. The deformation of the slab increases with decreasing h_l/h_{um} resulting in ocean-ward convex trench shape. Moreover, confirming what was already expressed by Morra *et al.* (2006), the widest are plates and the strongest is the trench bending.

The geodynamic mechanism

Contrasting models have been proposed so far to explain the coeval formation of the Gibraltar Arc and the Alboran basin. The more popular are: (1) backarc extension driven by the westward rollback of an eastward-subducting slab (Frizon de Lamotte *et al.*, 1991; Royden, 1993; Lonergan and White, 1997; Faccenna, *et al.*, 2004), (2) extensional collapse of an earlier collisional Betic-Rif orogen caused by convective removal of deep lithospheric roots (Platt and Vissers, 1989), (3) slab detachment or delamination of the lithospheric mantle (García-Dueñas *et al.*, 1992; Comas *et al.*, 1992; Seber *et al.*, 1996).

The geological and paleomagnetic constraints described in the above section, together with data from laboratory models, can be reconciled within a geodynamic framework for the western Mediterranean region dominated by the progressive westward rollback of the Tethyan subduction, and a back-arc extensional setting enhancing the formation of the Alboran Sea during the Neogene. Laboratory models showed that narrow\thin\heavy plates favour the retreating mode in a subduction system. Hence, the geometric and rheological features of the subducting lithosphere are a primary cause of the peculiar kinematics of the western Mediterranean subduction zone. In this area, the retreating mode of subduction is also favoured by the low average net convergence of the incoming plate at the trench (few mm/yr; i.e., Dewey *et al.*, 1989). The efficient lateral slab migration produced by a narrow slab-like the Gibraltar one is able to trigger in the mantle two symmetric toroidal return-flow cells centred close to the plate edges. As a consequence of such a process, the subducting plate progressively acquires a curvature that is always concave toward the trench. Even if laboratory models have been performed only using a subducting plate and are not able to model how the toroidal flow is transmitted to the overriding plate, the correspondence between the sense of the toroidal flow in the mantle induced by slab retreat, and the sense of vertical axis rotations measured in the upper plate along the two arms of the arc, strongly support the idea that roll back of a narrow slab is a valuable mechanism to generate the progressive curvature of the Gibraltar Arc.

Concerning the timing of the Gibraltar Arc bending, paleomagnetic results from Upper Miocene sediments in the Betics and in the Rif imply a revaluation of the age of acquisition of the curvature in the Gibraltar Arc. Actually, the bending of the Arc continued after the late Miocene throughout significant (about 20°-30°) opposite vertical axis rotations in the Betics (CW) and in the Rif (CCW). Concerning the upper limit for the age of such paleomagnetic rotations, useful information can be obtained comparing paleomagnetic and GPS results. The regional present-day kinematics of the western Mediterranean region is characterized by a small west-northwest motion of the Nubia plate respect to the Eurasia plate (»5 mm yr^{-1}). Such oblique convergence is accommodated in a region located between southern Iberia and northern Morocco (Fadil *et al.*, 2006), where a complex pattern of deformation, mainly characterized by strike-slip faults, is described by seismicity and GPS results. In this framework an active west-directed rollback of an east-dipping slab, which should cause a westward motion of Gibraltar relative to Africa, appear inconsistent with the well-defined eastward motion of GPS sites observed in north-western Morocco (Fadil *et al.*, 2006).

Conclusions

Based on the revision of the available structural and paleomagnetic data coupled with results from laboratory models on oceanic subduction, we suggest that the curvature of the Gibraltar Arc has been achieved throughout opposite vertical axis rotations on the two arms of the arc. Such paleomagnetic rotations have been measured in the late Miocene sediments both in the Betics and in the Rif chain, providing a significant rejuvenation of the age of vertical axis rotation. Laboratory models show that a trench roll back mechanism of a narrow subducting lithosphere can be a valuable mechanism to generate curved structures, mainly caused by toroidal return flow in the upper mantle. Such mechanism can be also extended to other Mediterranean arcs, such as the Calabrian Arc, where a clear relationship between trench-retreat and arc bending has been largely accepted.

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